ELSEVIER

Artificial Intelligence in Medicine 21 (2001) 139–146

Artificial Intelligence in Medicine

www.elsevier.com/locate/artmed

The Section on Medical Expert and Knowledge-Based Systems at the Department of Medical Computer Sciences of the University of Vienna Medical School

Klaus-Peter Adlassnig*

Department of Medical Computer Sciences, Section on Medical Expert and Knowledge-Based Systems, Spitalgasse 23, A-1090 Vienna, Austria

Received 30 June 2000; received in revised form 14 July 2000; accepted 1 August 2000

Abstract

The Section on Medical Expert and Knowledge-Based Systems at the Department of Medical Computer Sciences pursues methodological research in and practical development of knowledge-based computer systems to assist in the decision-making processes for all areas of medical application. Vagueness of medical terms, uncertainty in the co-occurrence of medical entities, and incompleteness in medical theories are well-known characteristics of medical knowledge and ought to be considered in practically-used medical knowledge-based systems. We found that fuzzy set theory and fuzzy logic are powerful theories that model the above-mentioned characteristics. Fuzzy set theory and fuzzy logic were applied in the following systems: CADIAG-II and MedFrame/CADIAG-IV, FuzzyARDS, and FuzzyKBWean. CADIAG-II and MedFrame/CADIAG-IV are framework programs for consultation systems to aid in the differential diagnostic process in internal medicine. FuzzyARDS is an intelligent on-line monitoring program of data from patients with acute respiratory distress syndrome (ARDS) at an intensive care unit (ICU). It employs fuzzy trend detection and fuzzy automata. FuzzyKBWean is an open-loop fuzzy control program for optimization and quality control of the ventilation and weaning process of patients after cardiac surgery at the ICU. The above-mentioned computer systems have reached the state of extensive clinical integration and testing at the Vienna General Hospital. The obtained results show the applicability and usefulness of these systems.

Keywords: Internal medicine; Consultation system; CADIAG-II; MedFrame/CADIAG-IV; Intensive care unit (ICU); Fuzzy automaton; FuzzyARDS; Fuzzy trend detection; Fuzzy control; FuzzyKBWean

* Tel.: +43-1-40400-6669; fax: +43-1-40400-6667.
E-mail address: kpa@akh-wien.ac.at (K.-P. Adlassnig).

0933-3657/01/$ – see front matter
PII: S0933-3657(00)00078-6

1. Introduction

The Section on Medical Expert and Knowledge-Based Systems' aim is to develop computer systems for broadly applicable computer-based medical decision support in the hospital, the medical laboratory, the physician's office, and within telecommunication-based medical or health care information systems. Although the Section was officially founded in 1987, its thematic roots reach back to 1968, when a computer-assisted diagnostic system for differential diagnosis in hepatology and rheumatology based on symbolic logic and heuristic hypothesis generation was developed and successfully tested [1,2]. Presently, the work covers formal methodological research in the areas of patient data and medical knowledge representation, medical knowledge acquisition, medical knowledge base consistency checking, medical inference mechanisms and evidence aggregation procedures as well as methods to evaluate the system's accuracy and acceptability. Of special interest are integrating medical expert and knowledge-based systems into the various medical and health care information systems and offering these systems on the world wide web (www). We also carry out applied interdisciplinary research with our medical and clinical partners, develop our systems as fully functionally prototypes and employ them as operational systems in the cooperating institutions for long-term study purposes. Furthermore, we teach both medical and computer science students at the University of Vienna and the Technical University of Vienna about all aspects of medical expert and knowledge-based systems in medicine. To a certain extent, we offer technical and operational services to the wards, out-patient departments, and institutes of the University of Vienna Medical School and its main teaching hospital, the Vienna General Hospital.

Medical expert and knowledge-based systems are designed to give expert-level, problem-specific advice in the areas of medical data interpretation, patient monitoring, disease diagnosis, treatment selection, prognosis, and patient management. They capture and make available the knowledge of experts and — by applying that knowledge to patient data — emulate and assist in the decision-making behavior of medical and administrative personnel. Research in medical expert and knowledge-based systems and the development of such systems is most significant to the broad realm of quality assurance and cost containment in medicine. The growing complexity of the fund of knowledge makes the application of such systems more and more indispensable. Provided that they are used correctly, these systems can reduce much of the repetitive and specialized mental efforts made by the treating physician and enable him or her to devote his or her attention to the personal care of the patient.

Medical knowledge is processed by the computer systems on the basis of stored medical knowledge and the current medical and administrative data of a patient, the systems provide a range of alternative suggestions for the course of patient care. The purpose of these decision-oriented suggestions is as follows:

- To ensure medical quality and to possibly improve patient care;
- To provide comprehensive quality management with consideration of medical working processes and administrative conditions;
- To ensure the efficient and cost-oriented utilization of available medical, technical, personnel, and organizational resources.

The results of these research activities have impacted a large number of computer applications in medicine:

- *Clinical patient management*: helping monitor patient's measured and derived medical data and generate reminders, warnings, and alerts during the automatic processing of medical protocols and guidelines.
- *Laboratory medicine*: providing knowledge-based interpretive reports of laboratory test results and having alerting modules check for notifiable, noteworthy, contradictory, or otherwise remarkable laboratory data.
- *Anesthesia and intensive care*: building monitoring systems for disease prevention and early detection of diseases, observing entry criteria for therapies, and building knowledge-based adaptive control systems for medical devices.
- *Internal medicine*: providing knowledge-based filtering, abstraction, and aggregation of medical data considering their context-dependency and temporal course, offering broadly applicable consultation systems for differential diagnosis and therapy to the caring physician in difficult cases, and providing electronic text tools for rare syndromes and rare pathological constellations with knowledge-based searching routines.
- *Image generating and processing medicine*: introducing systems for knowledge-based navigation and monitoring of diagnostic and surgical procedures including routines to avoid undesired events or anatomical regions, displaying differential diagnostic support during image interpretation, and offering clinical data of patients with preceding knowledge-based filtering to assist the image-diagnosing physician in his or her decision.

The Section on Medical Expert and Knowledge-Based Systems cooperates with institutions of the public sector and commercial partners to transfer its developed prototypes — usually after having been tested practically and studied extensively at the Vienna General Hospital — to other medical institutions.

In building medical expert and knowledge-based systems, special emphasis is put on the utilization of fuzzy set theory and fuzzy logic as methodology underlying the chosen patient data and medical knowledge representation and inference procedures. These methodologies have a number of characteristics that make them highly suitable for modeling uncertain information, which medical concept forming, patient state interpretation, and diagnostic as well as therapeutic decision making is usually based upon. First of all, medical entities such as symptoms, signs, test results, diseases and diagnoses, therapy proposals, and prognostic information items can be defined as fuzzy sets. The inherent vagueness of these entities will thus be conserved. Secondly, fuzzy logic offers reasoning methods capable of drawing strict as well as approximate conclusions. Medicine demands such a broad range of possibilities because the body of medical theory includes definitional, causal, statistical, and heuristic knowledge. Practical medicine even has to accept incomplete medical theories where only vague and uncertain empirical information guides the medical decisions and the diagnostic and therapeutic procedures they are based upon. Finally, fuzzy automata can be used as high-level patient monitoring devices employing real time access to the various medical information systems, such as hospital information systems (HIS), laboratory information systems (LIS), patient data management systems (PDMS), and others.

2. CADIAG-II and MedFrame/CADIAG-IV: computer-assisted diagnosis in internal medicine

The computer-assisted diagnostic (CADIAG) projects are long-term efforts aimed at building consultation systems able to extensively assist in the differential diagnostic and eventually in the therapeutic process in internal medicine. CADIAG-II, a consultation system formally based on fuzzy set theory and fuzzy logic, was developed and practically tested in 1979/80 [3]. The underlying clinical issues of CADIAG-II are

- indication of all possible disease hypotheses that can explain the given symptoms from the patient history, signs from the physical examination, pathological test results gained in the laboratory, and findings from clinical investigations such as ultrasonography, radiography, biosignal tests, endoscopy, and histology;
- proposals for further useful questions to and examinations of the patient to confirm or exclude gained diagnostic hypotheses or to find corroborative or discorroborative support for them;
- search for pathological findings present in the patient that are not yet accounted for by CADIAG-II's diagnostic hypotheses, then triggering the continuation of the differential diagnostic process — possibly in another medical area — until all pathological findings in the patient are being explained.

CADIAG-II was described at various stages of development [4,5] and applied in different areas of internal medicine [6,8,14]. It is fully integrated into the medical information system (Wiener Allgemeines Medizinisches Informationssystem, WAMIS) of the Vienna General Hospital [7].

MedFrame/CADIAG-IV is the present successor of the former CADIAG systems. MedFrame is intended to build a broad platform for the development of various knowledge-based systems in medicine: differential diagnosis or differential therapy in the entire field of internal medicine, for subspecialty areas of internal medicine such as cardiology, angiology, gastroenterology, hepatology, nephrology, rheumatology, pulmology, neurology, endocrinology, metabolic diseases, or for smaller portions of medicine such as differential diagnosis of abdominal pain, headaches, vertigo, or similar. It can host knowledge-based systems for the interpretive analysis of laboratory test results too. An integrated patient data and medical knowledge base, knowledge base editor modules, differential diagnosis and therapy modules, and an immediate case evaluation module will form the core of MedFrame. MedFrame/CADIAG-IV will be upward compatible with respect to the available medical knowledge bases contained in the former CADIAG systems. Improved data-to-symbol conversion with extended context dependency, stepwise abstraction of high-level medical concepts including temporal concepts, extended frame and rule-based knowledge representation, inference procedures able to infer positive and negative diagnostic hypotheses as well as positive and negative therapy proposals are characteristics of MedFrame/CADIAG-IV. Descriptions of parts of the system can be found in [9,10,11,13,15].

The development of the CADIAG systems, the integration of CADIAG-II into the medical information system WAMIS, and their extended retrospective and prospective case evaluations with patient records from the Vienna General Hospital form a broad basis

of theoretical and practical knowledge to develop a new and extended system for the ambitious task to assist the mental diagnostic and therapeutic activities of physicians, nurses, and laboratory personnel. The MedFrame/CADIAG-IV system — presently in an active development phase — will finally make a huge step towards decision-making support and computer-based automation of subareas of medical practice.

3. FuzzyARDS: knowledge-based monitoring and decision support

FuzzyARDS/MONITOR is an intelligent on-line monitoring program for the intensive care data of patients with acute respiratory distress syndrome (ARDS) [22]. Its clinical aim is to detect ARDS in patients as early as possible and to give appropriate therapy advice.

ARDS is an ill-defined medical entity and is modeled using the concept of fuzzy automata. States in these automata are considered to be a patient's pathophysiological state or entry criteria for different forms of ARDS therapies. Patients may be partially assigned to one or several states in such an automaton at the same point in time. Transitions in the automata carry fuzzy conditions that have to be true or partially true to transit from one state to another. Fuzzy conditions are usually high-level medical concepts such as low, normal, or high F_iO_2, hypoxemia, or linguistically expressed trend information, e.g., rapidly improving oxygenation. These high-level concepts are permanently evaluated in a data-to-symbol conversion step according to an adjustable time granularity. An extended description of these formal concepts can be found in [18,19].

In the present phase of development, an international study has been conducted to compare and finally improve the various forms of ARDS definitions found at the medical study centers and compare their respective entry criteria used for therapy decision. A web-based system called FuzzyARDS/STUDY was programmed allowing patient data entry at the study centers, the definition of fuzzy criteria, the calculation of fuzzy scores with respect to fuzzy criteria in the various stages of illness, and patient data evaluations based on interval techniques to consider missing variables in the given patient data sets. Most of the work done so far is described in [21,23].

Based on the available FuzzyARDS/STUDY system, patient data sets are entered at the various study centers and evaluated in ARDS consensus meetings. The results yielded to better understanding of ARDS as a life threatening disease and of its treatment [22]. Based on these results, FuzzyARDS/MONITOR is continuously adjusted to new derived medical knowledge. A prototypical application of FuzzyARDS/MONITOR is available for clinical tests [20]. Some problems have still to be solved, e.g., the definition and incorporation of idle and delay functions in the on-line monitor to avoid oscillations in the patient states.

4. FuzzyKBWean: knowledge-based weaning from artificial ventilation

FuzzyKBWean is an open-loop fuzzy control system for optimization and quality control of the ventilation and weaning process of patients after cardiac surgery at one of the ICUs of the Vienna General Hospital. The system is directly connected to the PDMS of the ICU and runs on the bed-side computers, as is described in [17]. In 1 min intervals, it

actively accesses the PDMS data base and transfers the patient's medical data necessary for ventilation and weaning decisions.

According to the well-known structure of fuzzy control systems, a fuzzification step is followed by the fuzzy rule evaluation. The fuzzy rules in FuzzyKBWean contain linguistically expressed physiological parameters of the patient and actual ventilator settings in their antecedents, yet crisp proposals for new settings of the ventilator in the consequences of the rules. The application of the Sugeno control method to combine rule output of the same kind is thus possible [16]. Moreover, a fuzzy set and fuzzy rule editor, called FuzzyKBWEdit, has been programmed that puts the cooperating physicians in the position to carry out knowledge base changes directly at the ICU ward.

An early study of FuzzyKBWean was published in [12]. A recent clinical trial showed that a number of appropriate proposals for ventilator settings are given at stages of the weaning process, earlier than the attending personal would react. Thus, the proposed adjustments to stabilize the ventilated patient, to start and end the weaning process, and finally to extubate the patient yielded to less suffering by the patient and a lower cost.

5. Future directions

Our research group will continue to develop formal and practical methods for building medical expert and knowledge-based systems. At present, research for evaluation study design for both accuracy and acceptability studies are becoming increasingly important because several systems developed by our group in cooperation with clinical partners, the City of Vienna, and the Vienna-based software company Software Unlimited DatenverarbeitungsGes.m.b.H. have already been operational at the Vienna General Hospital and other medical institutions or are going to be deployed. A medical knowledge base server offers some of them via www (address below).[1]

In this context, fuzzy set theory and fuzzy logic provide a highly suitable and broadly applicable basis for developing medical expert and knowledge-based systems in medicine, where the tasks include interpretation of sets of medical findings, single or differential diagnosis of diseases in various areas of medicine, optimal selection of medical therapy, and real-time monitoring of patient data for various purpose.

The clinical studies conducted show the appropriateness of the respective patient data and fuzzy knowledge representation and the selected fuzzy inference mechanisms with respect to the necessary medical applicability and the achieved correctness of the results. They further revealed the immediate intuitive understanding of the basic ideas of fuzzy set theory and fuzzy logic by the medical users. So, it is easily understood that the transition from healthy to ill and from normal to pathological, which is modeled by fuzzy sets in the above-mentioned knowledge-based systems, is a gradual transition and not a crisp one, and that the partial firing of rules with partially valid antecedents naturally diminishes the validity of the resulting consequence — a mechanism inherent to fuzzy logic.

[1] www links: http://www.akh-wien.ac.at/mes (homepage of the Section on Medical Expert and Knowledge-Based Systems). http://medexpert.imc.akh-wien.ac.at (medical knowledge base server of the Section on Medical Expert and Knowledge-Based Systems).

Fuzzy set theory and fuzzy logic in medical expert and knowledge-based systems will become a standard methodology of medical computer systems with computational intelligence. Eventually, there will be a time when medical expert and knowledge-based systems will be ubiquitously applied as natural tools in any medical setting.

Acknowledgements

Our work would not have been possible without the cooperation of our medical partners, some of whom lasted for more than two decades. First and foremost, we acknowledge Professors G. Kolarz, G. Grabner, W. Horak, W. Scheithauer, and Dr. H. Leitich for their immense work in building practically useful medical knowledge bases in several areas of internal medicine. Professors M. Hiesmayr and H. Steltzer, who are both anaesthesiologists and intensive care specialists, found the ideas of knowledge-based systems challenging and made knowledge-based applications at the ICU possible. We are highly indebted to the many students of computer science, electrical engineering, applied mathematics, and medicine doing their Master, Ph.D., or MD Theses on these matters, to the associates working in our group for a shorter or longer period of time (special thanks go to Drs. G. Kolousek, K. Boegl, Th. Rothenfluh, and L. Brein for their contributing work on MedFrame/CADIAG-IV, to Dr. F. Steimann and B. Trummer for their work on FuzzyARDS, and to Dr. Ch. Schuh, who leads and has realized the FuzzyKBWean project), to the many long-term helping hands and souls (special thanks to I. Gröger for extended help in CADIAG-II); they all accomplished impressive work.

References

[1] Bauer P, Brunner H, Michalek P, Paumgartner G, Richter H, Stöger H, Grabner G. Computerdiagnostik in der Hepatologie. In: Fellinger K, editor. Computer in der Medizin — Probleme, Erfahrungen, Projekte. Wien: Verlag Brüder Hollinek, 1968. p. 222–31.

[2] Horak W, Michalek P, Richter H, Thumb N. Computerdiagnostik in der Rheumatologie. In: Fellinger K, editor. Computer in der Medizin — Probleme, Erfahrungen, Projekte. Wien: Verlag Brüder Hollinek, 1968. p. 232–7.

[3] Adlassnig K-P. A fuzzy logical model of computer-assisted medical diagnosis. Methods Inform Med 1980;19:141–8.

[4] Adlassnig K-P. Fuzzy set theory in medical diagnosis. IEEE Trans Syst Man Cybernetics 1986;16:260–5.

[5] Adlassnig K-P. Uniform representation of vagueness and imprecision in patient's medical findings using fuzzy sets. In: Trappl R, editor. Cybernetics and Systems'88. Dordrecht: Kluwer Academic Publishers, 1988. p. 685–92.

[6] Adlassnig K-P, Akhavan-Heidari M. CADIAG-2/GALL: an experimental expert system for the diagnosis of gallbladder and biliary tract diseases. Artif Intell Med 1989;1:71–7.

[7] Adlassnig K-P, Kolarz G, Scheithauer W, Grabner H. Approach to a hospital-based application of a medical expert system. Med Inform 1986;11:205–23.

[8] Adlassnig K-P, Scheithauer W. Performance evaluation of medical expert systems using ROC curves. Comput Biomed Res 1989;22:297–313.

[9] Boegl K. Design and implementation of a web-based knowledge acquisition toolkit for medical expert consultation systems. Dissertation, Technical University of Vienna, Vienna, 1997.

[10] Boegl K, Leitich H, Kolousek G, Rothenfluh T, Adlassnig K-P. Clinical data interpretation in MedFrame/CADIAG-4 using fuzzy sets. Biomed Eng Appl Basis Commun 1996;8:488–95.

[11] Brein L, Adlassnig K-P, Kolousek G. Rule base and inference process of the medical expert system CADIAG-IV. In: Trappl R, editor. Cybernetics and Systems '98. Vienna: Austrian Society for Cybernetic Studies, Schottengasse 3, A-1010, Vienna, Austria, 1998. p. 155–9.
[12] Hiesmayr M, Gamper J, Neugebauer T, Mares P, Adlassnig K-P, Haider W. Clinical application of patient data management systems (PDMS): computer-assisted weaning from artificial ventilation (KBWEAN). In: Lenz K, Metnitz PGH, editors. Patient Data Management in Intensive Care. Wien: Springer, 1993. p. 129–38.
[13] Kolousek G. The system architecture of an integrated medical consultation system and its implementation based on fuzzy technology. Dissertation, Technical University of Vienna, Vienna, 1997.
[14] Leitich H, Adlassnig K-P, Kolarz G. Development and evaluation of fuzzy criteria for the diagnosis of rheumatoid arthritis. Methods Inform Med 1996;35:334–42.
[15] Rothenfluh TE, Bögl K, Adlassnig K-P. Representation and acquisition of knowledge for a fuzzy medical consultation system. In: Szczepaniak PS, Lisboa PJ, Tsumoto S, editors. Fuzzy Systems in Medicine. Heidelberg: Springer, 2000: 636–51.
[16] Schuh Ch. Wissensbasierte Entwöhnung vom Respirator unter Verwendung von Fuzzy- und Nichtfuzzy-Regelungsmodellen. Dissertation, Technical University of Vienna, Vienna, 1998.
[17] Schuh Ch, Hiesmayr M, Adlassnig K-P, Zelenka Ch, Klement EP. Integration of crisp- and fuzzy-controlled weaning in an ICU PDMS. In: Proceedings of the World Automation Congress, WAC '98, Albuquerque: TSI Press, 1998. p. 299–304.
[18] Steimann F. The interpretation of time-varying data with DIAMON-1, Artif Intell Med 1996;8:343–58.
[19] Steimann F, Adlassnig K-P. Clinical monitoring with fuzzy automata. Fuzzy Sets Syst 1994;61:37–42.
[20] Steimann F, Adlassnig K-P. Two-stage interpretation of ICU data based on fuzzy sets. In: AI in Medicine: Interpreting Clinical Data, Stanford 1994 Spring Symposium Series American Association for Artificial Intelligence, Stanford University, 1994: 152–6.
[21] Steltzer H, Fridrich P, Steimann F, Rossaint R, Adlassnig K-P, Hammerle A. Definition of severity and compiling of entry criteria in patients undergoing ECLA: the use of a fuzzy logic expert system. Acta Anaesth Scand 1996;40(Suppl 109):125–6.
[22] Steltzer H, Trummer B, Höltermann W, Kolousek G, Fridrich P, Lewandowski K, Adlassnig K-P, Hammerle AF. Wissensbasierte Diagnostik und Therapieempfehlung mit Methoden der Fuzzy-Set-Theorie bei Patienten mit akutem Lungenversagen (ARDS). Anästhesiologie Intensivmedizin Notfallmedizin Schmerztherapie 1999;34:218–23.
[23] Trummer B, Steltzer H, Kolousek G, Adlassnig K-P, Hammerle AF. Knowledge-based definition of ARDS therapy entry criteria using fuzzy set theory. Acta Anaesth Scand 1998;42(Suppl 112):238–9.